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Flexible ZIFs: probing guest-induced flexibility with CO₂, N₂ and Ar adsorption

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Abstract

BACKGROUND: The effect of framework topology on the guest-induced flexibility of several crystalline zeolitic imidazolate frameworks (ZIF-7, ZIF-9, ZIF-11 and ZIF-12) was investigated via analysis of experimental nitrogen (N₂), carbon dioxide (CO₂) and argon (Ar) isotherms at 77 K (N₂ and Ar) and 273 K (CO₂) for gas pressures up to 0.13 MPa.

RESULTS: The experimental isotherms of these frameworks were analysed in order to investigate their structural flexibility using gases with kinetic diameters equal to or larger than the diameters of their static pore apertures. The results of gas sorption measurements indicate guest-induced phase changes for ZIF-7 and ZIF-9 (SOD topologies). ZIF-12 (RHO topology) also shows uptake for gases, despite its pore-limiting diameter being smaller than the kinetic diameters of the adsorbed molecules.

CONCLUSIONS: This work highlights the ability of ZIFs with different framework topologies to change their structure and increase their pore aperture upon interaction with certain gases. These findings are key in the development of more selective ZIF-based materials for important industrial applications including low-energy gas separations, catalytic nanoreactors and sensor technology.

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Keywords: gas adsorption; MOF; ZIF; flexibility; breathing structure; nanomaterials

INTRODUCTION

Metal–organic frameworks (MOFs) have been heavily researched as adsorbents in a variety of applications that include gas storage, gas separation and catalysis. This is due mainly to their large accessible surface areas (in comparison to materials such as activated carbons, zeolites and porous polymers), permanent porosities and tuneable structures.^{1–3} MOFs are crystalline materials composed of organic linkers connecting metal clusters, with open channels that range in size from the micropore (<2 nm diameter) to the mesopore scales (2–50 nm in diameter).⁴ Due to their crystalline structures, MOFs can be easily characterized using X-ray diffraction (XRD) techniques, making their identification relatively straightforward.^{2,3}

The ZIFs (zeolitic imidazolate frameworks) are a subclass of MOFs that have structures resembling those of zeolites.^{5,6} They incorporate imidazoles as organic linkers, connected with metal clusters [e.g. zinc (Zn), cobalt (Co)], forming a 145° angle, similar to the 145° silicon (Si)–oxygen (O)–Si angle found in zeolites.⁵ Almost 30 different zeolite topologies also have been reported for ZIFs.^{7,8} Materials with certain topologies, such as SOD and RHO, have shown extraordinary thermal and chemical stability, being even able to resist boiling aqueous alkaline solutions and organic solvents.^{5,9} ZIF materials with SOD topologies are composed of truncated beta cages (cuboctahedrons), comprising windows of four- and

six-membered rings having 24 Co or Zn atoms per unit cell, with a cubic arrangement of interconnected beta cages.^{5,7,8,10} ZIF materials with RHO topologies consist of alpha cages, with windows comprising four-, six- and eight-membered rings, having 48 Zn or Co atoms per unit cell. Each alpha cage is connected to the six neighbouring alpha cages through polyhedral units comprising double eight-membered rings (known as D8R).^{5,7,8,10} Recently, it was shown that ZIFs could retain their chemical configuration, bonding and porosity when melted, showing that these MOFs also can exist in the liquid state.¹¹

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ZIFs have been the subject of much attention due to the flexible behaviour of the framework structure, which can be induced by either guest molecule adsorption, temperature or pressure changes. Flexible MOFs are interesting in various applications, with the most prominent being gas separation and sensor technology. ZIF-8 has shown notable framework flexibility under very high pressure with adsorption of guest molecules, which has been associated with the rotation of the imidazole linkers.¹² ZIF-7 (SOD topology) also has shown a sorbate-induced gate-opening phenomenon, which was first demonstrated by Aguado et al., with the adsorption of CO₂.¹³ This gate-opening phenomena involved a narrow-to-large pore phase transition, which was then further confirmed with C2–C4 alkane/alkene adsorption.^{14,15} This structural change was subsequently studied using high-resolution neutron diffraction, and the analysis showed the importance of the rotation of the benzimidazole linkers.¹⁶ The pore windows of ZIF-7 are c.0.29 nm in the small pore configuration and can allow molecules of 0.52 nm in diameter when they are in the large-pore phase.¹⁷ Carbon dioxide (CO₂) is adsorbed primarily in two small cavities formed by the benzimidazole linkers in the six-membered rings of Zn atoms, which rotate upon CO₂ adsorption and open the cavities to accommodate further CO₂ molecules.¹⁶ These phase transitions were investigated, and at least three different phases for ZIF-7 were identified.¹⁸ The behaviour of ZIF-7 also has been recently suggested to be more complex than initially thought, as temperature also can drive phase changes in the structure, with ZIF-7 undergoing a phase change from narrow pore to large pore at 973 K in vacuum or at 773 K in CO₂ or N₂.¹⁹ Interestingly, in this study ZIF-7 also showed a second step at higher CO₂ pressures at low temperatures (i.e. at 196 K, 206 K and 263 K) which doubled the CO₂ loading.¹⁹ This second step was reported in the paper to be associated with the rearrangement of CO₂ molecules in the pores of the large-pore phase. More recently, methane (CH₄) also was shown to induce gate-opening in ZIF-7, with the transition estimated at 1245 kPa for CH₄ and 78 kPa for CO₂, both at 303 K.¹⁷ This reversible transition also was assigned to the flexibility of the benzimidazole linkers, which enable a large-pore phase that can allow molecules of 0.52 nm diameter to enter the main cavities. In addition to CO₂ and CH₄, other molecules have been shown to induce a phase-change in ZIFs – in our past work we have shown this effect for hydrogen (H₂) adsorption in ZIF-7 and ZIF-9,²⁰ and other reports showed phase changes upon adsorption of ethane, ethylene, propane, propene, butane and butene in ZIF-7.^{15,21} Other ZIF materials have been investigated for the phase transition seen in ZIF-7 using CO₂ adsorption, such as ZIF-11, ZIF-93 and ZIF-94, a group of ZIFs that combine RHO and SOD topology, but the only ZIF material that showed a phase transition was ZIF-7.²² In our previous work, we showed that ZIF-9 (SOD topology), which only differs from ZIF-7 in the nature of the metal cluster (Co rather than Zn), also showed the same features as ZIF-7 upon the adsorption of hydrogen at 77 K and at 1 MPa.²⁰ To our knowledge, no CO₂ adsorption has been measured on this material. There is much interest in further exploring the phenomena and defining the flexible responses in order to apply them in specific technology fields such as in gas separations, microsensors, micromechanical devices, and nanomedicine or catalytic nanoreactors.²³

In the present paper, we investigate CO₂, N₂ and Ar adsorption in ZIF-7 (SOD), ZIF-9 (SOD), ZIF-11 (RHO) and ZIF-12 (RHO), with the goal of probing the flexible features in these structures. ZIF-7 and ZIF-9 share the same topology (SOD), but are made of different metal centres (Zn and Co), just as ZIF-11 and ZIF-12 share the same topology (RHO), but contain different metals (also Zn and Co).

EXPERIMENTAL

The materials were synthesized according to methodologies reported in the literature, using methanol (ZIF-12) and ethanol (ZIF-7, ZIF-9 and ZIF-11), but with their syntheses scaled-up to ensure that enough material was available for the experimental tests.⁷ Powder XRD measurements were run on a D8 Advance Diffractometer (Bruker, Billerica, MA, USA) using Cu-K α radiation, $\lambda = 0.154184$ nm, a lynxeye detector at 40 kV and 40 mA over a 2θ range of 0–40° with a step size of 0.041° s⁻¹ to confirm phase purity. Measurements were done in flat plate mode at 298 K on wet samples (methanol for ZIF-12, and ethanol for ZIF-7, ZIF-9 and ZIF-11), with the solvents used in several cycles to wash the samples. Experimental powder XRD spectra were compared against the original CIF files obtained from the Cambridge Crystallographic Database as well as the literature, in order to ensure the correct synthesis of the materials, details of which can be found in our previous work.^{7,20} The XRD spectra for ZIF-7 and ZIF-9 are shown in Fig. 1, and the XRD spectra for ZIF-11 and ZIF-12 are shown in Fig. 2. Differences in the calculated and experimental XRD patterns have been attributed to the effect of different solvent washing cycles on the XRD spectra.⁷

We previously investigated the stability of the synthesized materials in order to determine degassing conditions.²⁰ These were performed on a Setaram TGA 92 16.18 (Setaram, Caluire, France), with the materials heated at 5 K min⁻¹ from 293 to 873 K in flowing, dry N₂ at 1 bar. Degassing temperatures were thus determined to be 473, 498, 523 and 573 K for ZIF-7, ZIF-9, ZIF-11 and ZIF-12 respectively (see the Supporting Information for a summary of the data). For adsorption tests using N₂ at 77 K, Ar at 77 K and CO₂ at 273 K, an Autosorb 1-MP (Quantachrome Instruments, Boynton Beach, FL, USA) and a Micromeritics ASAP 2020 (Micromeritics Instrument Corporation, GA, USA) were used. The gas sorption analyses were performed on ~100 mg samples degassed under dynamic high vacuum (10⁻⁷ mbar) at the temperatures noted above, before analysis. It should be noted that the Ar characterization was done at 77 K, whereas the IUPAC methodology for characterization of porous materials recommends that Ar analysis should be done at 87 K.²⁵ This is due to the sensitivity of the Ar cross-sectional area to the temperature, as at 77 K the Ar monolayer is highly dependent on the structure of the adsorbent surface.²⁵ The main aim of the present work was to probe the structure of the ZIFs with different gases, investigating the interaction of the adsorbent with different probe gases. Unlike N₂, Ar has no quadrupole moment, is less reactive and interacts differently with adsorbents. As no significant adsorption occurred, and the Brunauer–Elmett–Teller (BET) areas for the materials given in SI calculated from Ar are to be taken with this in mind, the fact that the Ar adsorption was done at 77 K is less relevant.

In order to calculate BET surface areas, the standard method consistent with the 2015 IUPAC Technical Report and BS ISO 9277:2010, (which uses the consistency criteria reported by Rouquerol) was applied.^{25–27} To obtain the micropore volume and total pore volume of the materials, Dubinin–Radushkevich (DR) and Gurvich methodologies were used, respectively.^{28,29}

RESULTS AND DISCUSSION

A summary of the different pore diameters of the different materials and kinetic diameters of the different molecules involved in the analyses is shown in Table 1:

The CO₂ adsorption isotherms of both ZIF-7 and ZIF-9 (Figs 3 and 4) show a sudden CO₂ uptake between 10 and 20 kPa. ZIF-7

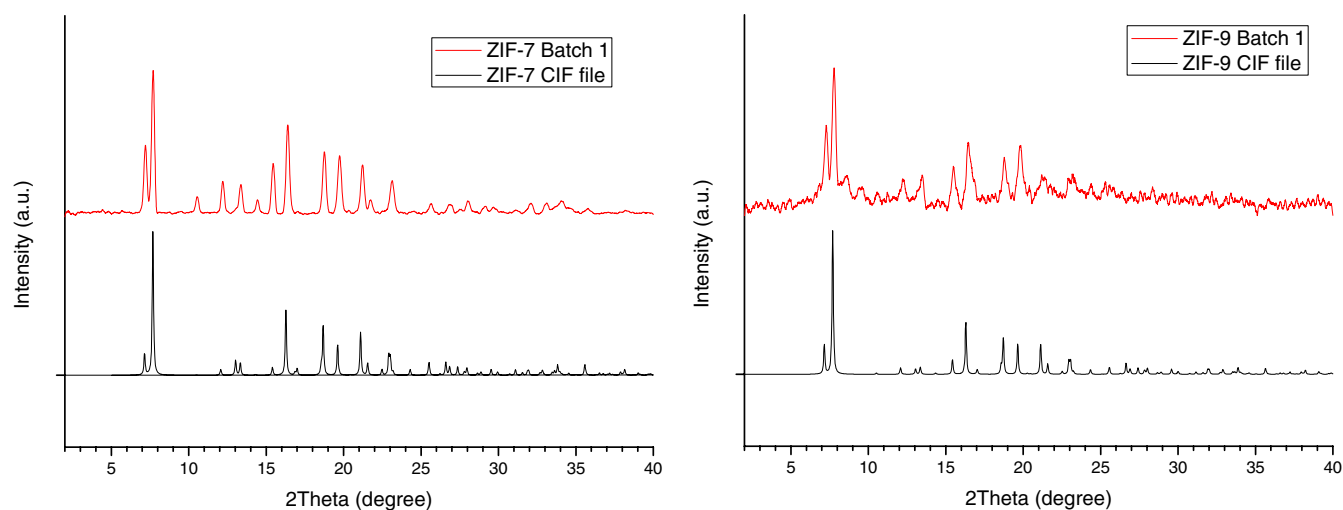


Figure 1. Powder XRD spectra of ZIF-7 (left) and ZIF-9 (right). The red spectrum is from the synthesized material and the black spectrum is generated from the CIF file from He et al.⁷ for ZIF-7 and Li et al. for ZIF-9.²⁴ Spectra have been offset in the y-axis for clarity.

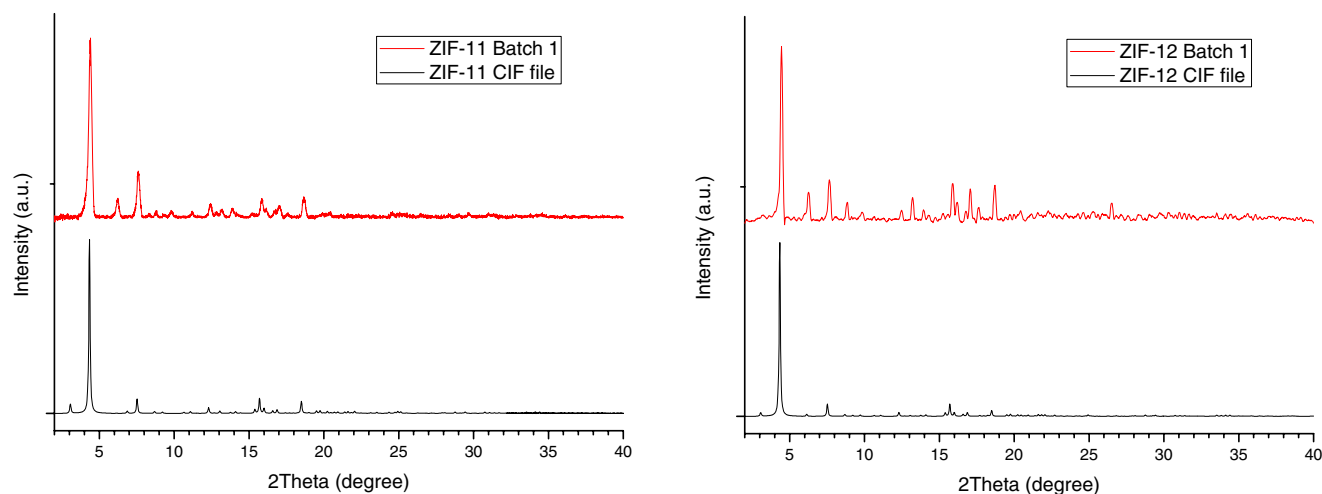


Figure 2. Powder XRD spectra of ZIF-11 (left) and ZIF-12 (right). The red spectrum is from the synthesized material and the black spectrum is generated from the CIF file from He et al. for both ZIF-11 and ZIF-12.⁷ Spectra have been offset in the y-axis for clarity.

Table 1. Summary of pore size and kinetic diameters of the different materials and molecules

Name	Pore size (ZIFs) or kinetic diameter (nm)	Reference
ZIF-7, ZIF-9	0.29	7
ZIF-11	0.30	7
ZIF-12	0.32	30
CO ₂	0.33	31
Ar	0.354	31
N ₂	0.364	31
Methanol	0.36	32
Ethanol	0.45	32

Adsorption isotherms with CO₂, N₂ and Ar are shown for ZIF-7 (SOD), ZIF-9 (SOD), ZIF-11 (RHO) and ZIF-12 (RHO) in Figs 3–5 and 6.

and ZIF-9 both show hysteresis in their desorption isotherms, and a step that is compatible with a sorbate-induced gate-opening phenomenon, a feature that has been widely reported in the

literature.^{13,14,20,33} Regarding the N₂ or Ar isotherms of ZIF-7 and ZIF-9 in Figs 3 and 4 (both with similar structural dimensions⁵), these barely show any adsorption, which can be due to the gases' high kinetic diameters (0.364 and 0.354 nm, respectively, for N₂ and Ar)³¹ compared to their pore window size (0.29 nm).⁷ CO₂, however, which has a kinetic diameter of 0.330 nm³¹ has been shown to be admitted into the framework. It has been shown that ZIF-7 can selectively separate ethane over ethylene,²¹ which have even bigger kinetic diameters (0.4163 and 0.4443 nm for ethylene and ethane, respectively³⁴), with both molecules inducing phase changes in the structure at different pressures. This indicates the ability of ZIF-7 to adsorb molecules with higher kinetic diameters, due to the existence of specific interactions present between ethane/ethylene and the ZIF-7 structure. Based on the results presented in Fig. 3, these interactions do not seem to be present in N₂ and Ar, as adsorption of these gases does not induce a phase change.

Figures 3, 4 and 6 show that ZIF-7, ZIF-9 and ZIF-12 exhibit similar maximum CO₂ adsorption capacities, with ZIF-7 showing 51 cm³ STP g^{−1} at c.105 kPa, followed by ZIF-12 with 48 cm³ STP g^{−1} and ZIF-9 with 44 cm³ STP g^{−1} at 105 and 120 kPa, respectively. These

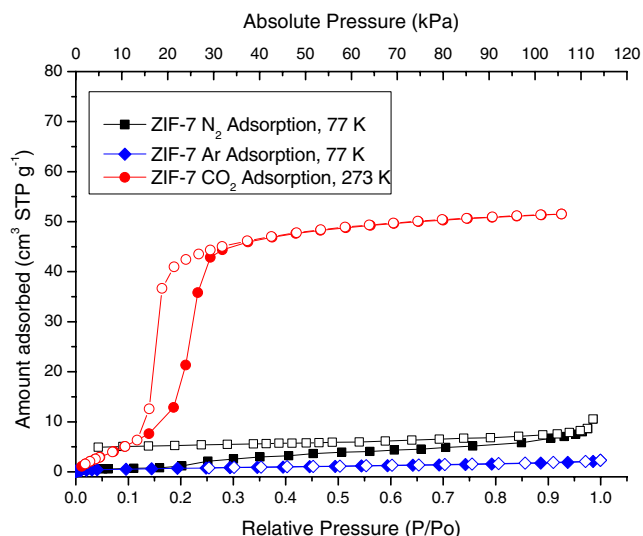


Figure 3. Adsorption isotherms of N₂ at 77 K, Ar at 77 K and CO₂ at 273 K on ZIF-7. Relative pressure refers to N₂ and Ar, whereas the absolute pressure axis refers to the CO₂ isotherm. Open symbols indicate desorption points.

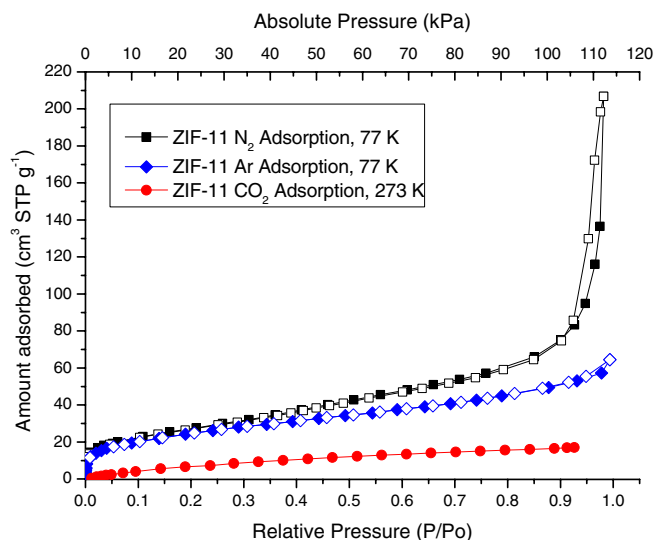


Figure 5. Adsorption isotherms of N₂ at 77 K, Ar at 77 K and CO₂ at 273 K on ZIF-11. Relative pressure refers to N₂ and Ar, whereas the absolute pressure axis refers to the CO₂ isotherm. Open symbols indicate desorption points.

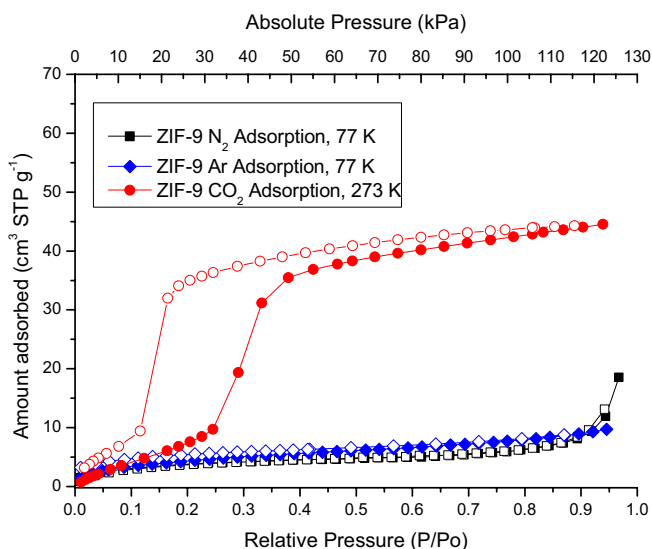


Figure 4. Adsorption isotherms of N₂ at 77 K, Ar at 77 K and CO₂ at 273 K on ZIF-9. Relative pressure refers to N₂ and Ar, whereas the absolute pressure axis refers to the CO₂ isotherm. Open symbols indicate desorption points.

results indicate very similar CO₂ adsorption capacities when compared to other ZIFs with GME topology (ZIF-68, ZIF-69, ZIF-81 and ZIF-82).^{9,35} The results in Fig. 4 also show the step associated with a phase change of the ZIF-9 framework structure. The only difference between ZIF-7 and ZIF-9 is the metal centre, which suggests a similar mechanism for this phase change, that is, a gate-opening effect upon adsorption of guest molecules. As seen for ZIF-7, this gate-opening is consistent with a rotation of the benzimidazole linkers which increases the diameter of the cavities and allows for increased adsorption of CO₂. A recent study by Cuadrado-Collados et al.³⁶ highlighted the importance of complete solvent removal and equilibration times, and showed CO₂ to be less sensitive to the blocking effect of DMF. In that paper, N₂ was shown to be adsorbed by ZIF-7 under long equilibration times of 15 days. We should note that the synthesis of ZIF-7, ZIF-9 and ZIF-11 was carried

out with ethanol, and ZIF-12 was synthesized with methanol, and no DMF was used for the synthesis. As noted in the same paper by Cuadrado-Collados et al., an extended solvent exchange process with methanol is essential for a solvent-free structure.³⁶

ZIF-11 and ZIF-12 show CO₂ adsorption isotherms increasing progressively (Figs 5 and 6), indicating adsorption in the cavity that occurs without the limitation of the pore window size. The small differences in the biggest pore window are unlikely to explain the large differences seen for Ar and N₂ uptake between ZIF-11 and ZIF-12. As noted above, the differences in uptake are more likely because of the fact that ZIF-11 was exchanged with ethanol and ZIF-12 was exchanged with methanol, which, as noted by Cuadrado-Collados et al.,³⁶ is essential for obtaining a solvent-free structure. Our results further confirm this observation. In addition, these ZIFs, despite having the same topology and similar pore size apertures, present different N₂, Ar and CO₂ adsorption isotherms in terms of capacity and shape. Again, some care should be taken when interpreting these results, because the structure might not be completely solvent-free and, as shown for other ZIFs, there might be specific interactions between the adsorbate molecule and the framework structure. These results reflect the influence of different solvents, as ZIF-12, which was synthesized with methanol, showed considerable uptake of Ar and N₂, whereas ZIF-11, which was synthesized with ethanol, displayed much more modest uptakes. The higher uptake of Ar in comparison with N₂ might be due to the small difference in the kinetic diameters of the gases. The kinetic diameter of Ar is 0.354 nm and the kinetic diameter of N₂ is 0.364 nm, meaning that the difference is only 0.01 nm. However, given that the largest pore window of ZIF-12 is 0.32, such a small difference might be enough to explain the higher uptakes of Ar in comparison with N₂.

ZIF-11 and ZIF-12 have a difference of 0.02 nm in their biggest pore window diameter (eight- versus six- membered rings, 0.30 and 0.32 nm, respectively), which allows them to adsorb N₂ and Ar (0.364 and 0.354 nm). These results indicate that ZIF-11 and ZIF-12 also might possess flexible structures, as seen in ZIF-7 and ZIF-9. The fact that ZIF-11 and ZIF-12 have slightly larger pore sizes than ZIF-7 (0.30 and 0.32 versus 0.29 nm) suggests that the pore windows of ZIF-11 and ZIF-12 can stretch under no/low

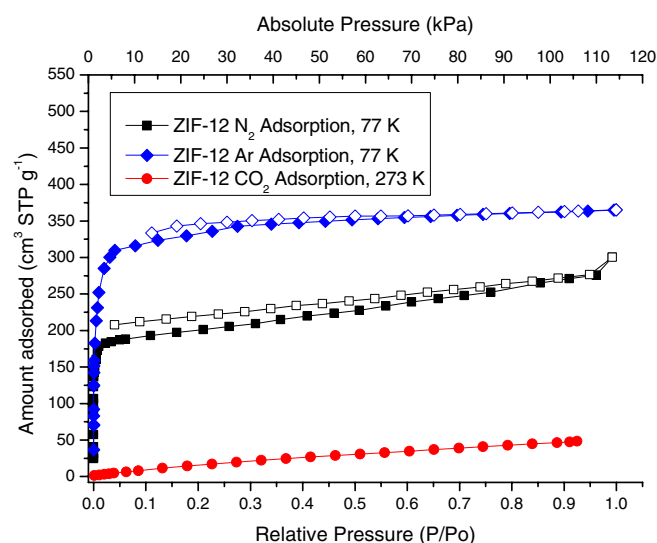


Figure 6. Adsorption isotherms of N_2 at 77 K, Ar at 77 K and CO_2 at 273 K on ZIF-12. Relative pressure refers to N_2 and Ar, whereas the absolute pressure axis refers to the CO_2 isotherm. Open symbols indicate desorption points.

electrostatic interactions to adsorb N_2 and Ar. The difference between the pore size of ZIF-7 and CO_2 is 0.04 nm, whereas the difference between ZIF-11 and N_2 is 0.064 nm, meaning that ZIF-11 appears to exhibit a higher degree of pore flexibility in adsorbing the gas molecule. This possible extra flexibility is attributed to the RHO topology. The RHO topology is formed of alpha cages composed of four-, six- and eight-membered rings (compared to the SOD, which is formed only by four- and six-membered ringed beta cages), and has two more benzimidazolate linkers on the larger pore windows to further open the pore windows of the framework.

Also, the mentioned smaller pore size and metal nature of ZIF-11 might explain some of the differences between ZIF-11 and ZIF-12 adsorption. It also is important to note that H_2 adsorption isotherms of ZIF-7 and ZIF-9 are very similar in shape and amount adsorbed,²⁰ but the results for ZIF-11 and ZIF-12 show no hysteresis or step in the adsorption isotherm that indicate phase changes with either H_2 or with any of the gases tested in this work.

From the adsorption isotherm data, the textural properties and pore-size distributions using the HK Cheng Yang DFT methodology^{37,38} have been obtained, and are shown in the Supporting Information. This textural information reflects all the above-mentioned discussion, where the most relevant results are the CO_2 BET (240 and 224 $m^2 g^{-1}$) and DR micropore volumes (0.11 $cm^3 g^{-1}$ for both using DR) of ZIF-7 and ZIF-9. The similarity in the surface area and pore volumes indicate similar CO_2 surface adsorption capacities and accessibility of the molecules into these ZIF frameworks. Conversely, N_2 adsorption data shows ZIF-12 to have a higher BET surface area than ZIF-11 (789 and 97 $m^2 g^{-1}$, respectively) and micro- and total pore volumes (0.32 and 0.46 $cm^3 g^{-1}$ from the DR and Gurvich methods for ZIF-12 and 0.03 and 0.30 $cm^3 g^{-1}$ for the DR and Gurvich for ZIF-11).

CONCLUSIONS

Adsorption isotherms for N_2 at 77 K, Ar at 77 K and CO_2 at 273 K were obtained and analysed for ZIF-7, ZIF-9, ZIF-11 and ZIF-12.

ZIF-7 and ZIF-9 showed CO_2 adsorption isotherms with hysteresis and a step, corroborating sorbate-induced gate-opening phenomena as shown in the literature. Although this has been studied and observed for ZIF-7, we observe the same effect for ZIF-9, which also is consistent with the rotation of the benzimidazolate linkers. This allows more CO_2 to be adsorbed in the cavities, as opposed to Ar and N_2 , which showed no significant adsorption. ZIF-12 and ZIF-11 (RHO topology) showed uptake for N_2 and Ar, which have larger kinetic diameters than the largest pore diameter in ZIF-11 and ZIF-12, also indicating pore flexibility due to the two additional benzimidazolate linkers in its structure. The differences in uptake of Ar and N_2 in ZIF-11 and ZIF-12, which were synthesized with ethanol and methanol respectively, also show the importance of using methanol as the solvent. As noted in the literature, methanol is essential for obtaining a solvent-free structure in ZIFs, and our results further confirm this observation. The similarities in the uptake behaviours between ZIF-7 and ZIF-9 indicate the over-riding influence of topology over the metal species in determining the uptake of different gas species in these ZIFs. The marked differences in framework flexibility between ZIFs with SOD and RHO topologies may aid in identifying other flexible zeolite topologies with similar potential to discriminate between gases of similar molecular size for applications in gas separation.

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Supporting Information

Supporting information may be found in the online version of this article.

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